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WNR Facility Flight Path 90L Advanced Collimation Development

In November 2020, an advanced neutron beam transport and collimation system was installed and commissioned at flight path (FP) 90L within the Weapons Neutron Research (WNR) facility. This new collimation system was developed as a replacement for the legacy neutron collimation present at WNR FP90L. The need for this upgrade, design of this collimation system, installation at the experimental flight path, and results of this recent effort will be detailed.

Background

Precision nuclear cross section measurements of short lived radioisotopes at WNR FP90L planned for the end of the 2020 run cycle require neutron beams having high flux, low background, uniform beam spots, and precise delivery. These unique reaction measurements will be executed at a newly developed flight path instrument, hotLENZ, installed in the 90L flight path located 8.25 meters away from the WNR spallation target. The stringent neutron beam requirements of the reaction measurements, combined with a long flight path length, establish the reality that the existing flight path collimation will not satisfy the needs of the experimental program. Therefore, a new collimation system was designed utilizing facility survey data, 3D modeling, and feedback from MCNP studies to deliver a neutron transport system which meets the needs of the upcoming reaction measurement, while seamlessly integrating with the newly developed hotLENZ instrument.

Overview

The groundwork for this effort was laid earlier in 2020 with the establishment of a facility wide unified spatial metrology network (USMN) and the installation of a second generation spallation target (T4GEN2) at the WNR facility (LA-UR-20-30500). Without a strong metrology network in the facility, precision knowledge of the absolute location of the WNR spallation target, and a clear understanding of the flight path layout within the bulk shield, we would not be capable of designing or fielding an advanced collimation system at this flight path. A comprehensive as-built 3D model of the WNR facility was derived from these prior efforts (Figure 1). Combining the geometry from this facility model with the newly designed hotLENZ instrument, planned radioactive sample geometry, and low background requirements of the detectors, the boundary conditions were set for the design of the collimation system. Ray tracing within the 3D model was employed to speed design iterations, and solid models were exported to MCNP for evaluation of neutron transport performance. Once the conceptual geometry of the collimation was established, the field of view was fixed and the nominal alignment of the collimation was determined. A precision alignment and support structure was designed for the new collimation, providing the required motions for alignment in 6 degrees of freedom (DOF). The 3D field of view data and nominal alignment data was then used to design a new shutter insert providing unobstructed neutron transport through the bulk shield while reducing background to the largest extent possible.

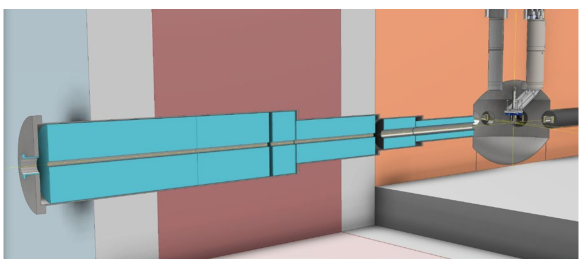

Figure 1. As-Built 3D Model of WNR FP90L

The entire system was fabricated with special attention to the individual collimation elements. They were precision machined via wire electrical discharge machining (EDM) to deliver the precision necessary for the collimation to perform as designed. The new shutter insert was the first component installed at the flight path and it took the place of the legacy shutter insert in the bulk shield. The collimation alignment and support structure was then installed with a preliminary alignment. The collimation elements were installed and precision aligned, establishing the neutron beam axis. Image plates were taken at the sample position and three meters downstream of the sample position. They were evaluated to verify neutron transport performance.

Collimation Design

The WNR spallation target is a solid cylinder of tungsten 30mm in diameter and 75mm long. Neutrons are emitted from the entire volume during the spallation process. Due to its size it cannot be simply treated as a point source, therefore each path a neutron may take from any point in its volume must be considered to maximize flux. Neutron collimation which is long and has a small opening can be, to first order, treated as if it were a pinhole camera, meaning it will project an "image" of the spallation target on the sample. It is important to note that the profile of the spallation target, when viewed from FP90L is a rectangle (Figure 2), so a short and wide beam spot is generated at 90L when the spallation target is within the entire FOV of the traditional collimation (Figure 3).

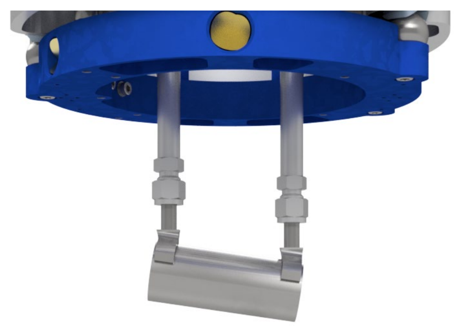

Figure 2. WNR Spallation Target as Viewed From FP90L

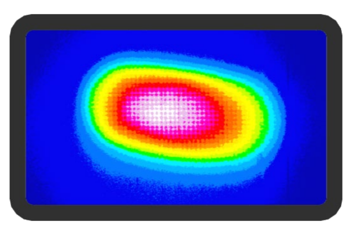

Figure 3. An Example of a Beam Profile at FP90L with Traditional Style Collimation

The samples which are utilized in the hotLENZ instrument are depositions of radioisotopes 6mm diameter electroplated on thin gold foil. This thin foil is mounted to an aluminum support frame with an inner diameter of 19.1mm (Figure 4). This creates the boundary conditions for the neutron beam spot we create at the sample position. The beam spot must drop off rapidly to not hit the aluminum sample frame, and the flux must be maximized and completely uniform over the 6mm sample area. To create such a beam spot with a circular geometry using a neutron source with a rectangular profile would be overly complicated when compared to creating a beam spot meeting these requirements having a square profile. It was decided that a square beam, 12.8mm on side, with a central 6mm square of max/uniform flux would be the design goal, rotated to 8.25° to match the inclination of the spallation target (Figure 4). Preliminary ray tracing combined with MCNP studies was completed to optimize the position of the sample while providing a thick enough collimator to be effective. The sample position was set to 8.25m

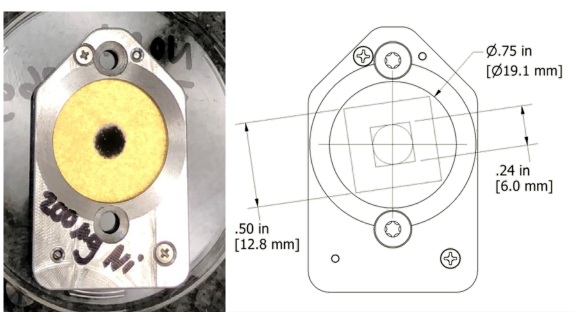

Figure 4. Typical Sample for hotLENZ Left, Nominal Beam Profile on Sample Frame Right

To set a benchmark for the design iterations, the theoretical maximum neutron flux was calculated via MCNP at the 8.25m target position using a 6mm square tally. This measure of the theoretical maximum flux used only the solid angle of the tally, as there were no additional elements in the study to hinder neutron transport from the spallation target. It was decided that a double tapered design would be used (Figure 5) to provide sharp cutoffs at the edges of the neutron beam penumbra. Also, the collimation geometry in the vertical direction would be designed independent of the geometry in the horizontal direction. When the pinhole camera approximation is applied, what the design will produce is a pinhole camera having a vertical image magnification which is different than the horizontal image magnification. This allows a "variable aspect ratio" collimator to be realized, enabling additional control over the profile of the delivered beam. Employing ray tracing to adjust the aspect ratio of the vertical and horizontal magnification allows the creation of a square image of a rectangular object. This is how the advanced collimation system under development will create a square beam spot from a rectangular neutron source.

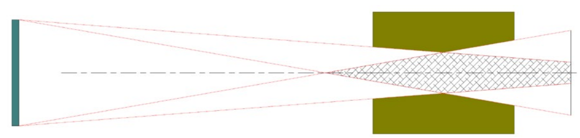

Figure 5. Example of Double Taper Collimation, Neutron Source Left, Sample Position Right, Hashed Area Indicates Fully Illuminated Portion of Beam at Sample Position

The maximum overall length of the collimation was determined using the available space between the hotLENZ chamber when positioned at 8.25m, and the FP90L shutter flange at the bulk shield. This envelope provides room for a collimation system of 1m to be installed. A 3D model was then built up with all of the boundary conditions: spallation target geometry, sample position, beam profile at sample position, the physical flightpath/instrument layout, and beam spot flux/background requirements. Ray tracing was done in 3D from the spallation target to the sample position to create a nominal envelope of allowed neutron trajectories (Figure 6.)

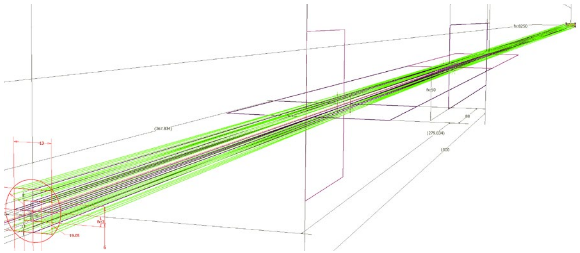

Figure 6. Perspective View of 3D Ray Trace, Sample Position Left, Spallation Target Right, 8.25m

The internal geometry of the collimation was dictated by this ray tracing and preliminary solid models were generated and exported to MCNP for studies. Several design iterations were completed to optimize the geometry and materials of construction, since there must be a compromise between flightpath length (solid angle - theoretical max flux on sample), collimation length (effective background suppression of unwanted neutron paths), and distance from collimation to sample (physical size of hotLENZ instrument). An offset double taper design emerged from this work, with the downstream most elements of the collimator fabricated from tungsten and the balance brass (Figure 7).

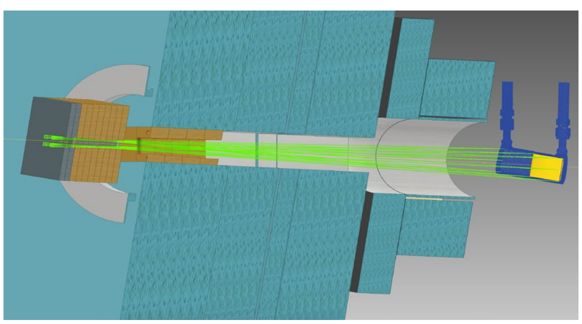

Figure 7. Orthographic Cut Away Model of the Final Collimator Geometry in the Flight Path at 90L

The disparity in the height/length ratio of the spallation target geometry combined with the design compromises made during collimation geometry optimization, forced the horizontal collimation component to have a double taper justified further downstream than the vertical component. MCNP studies (Figure 8) indicated that this comprise would manifest itself as lower performance of the horizontal penumbra cut-off at the sample frame (10^5) when compared to the vertical component (10^7).

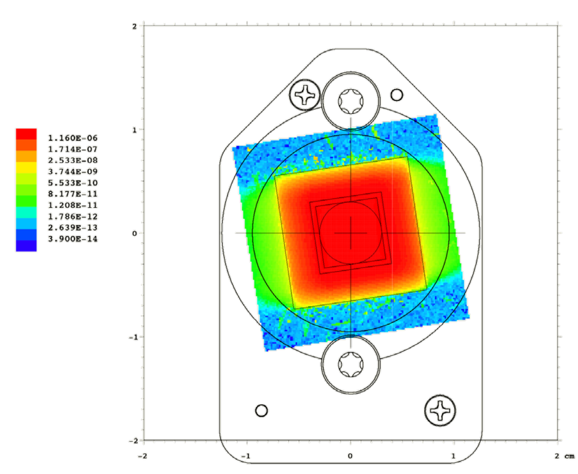

Figure 8. MCNP Study of Final Collimation Design, Visualization Covering 8 Orders of Magnitude

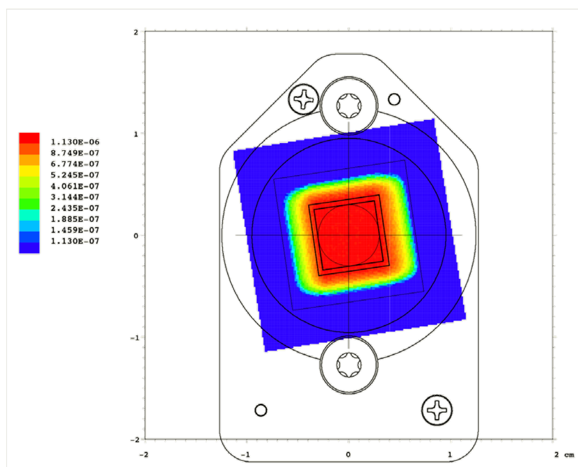

Figure 9. MCNP Study of Final Collimation Design, Visualization above 1/10 Theoretical Max

Further analysis of the MCNP studies confirmed the successful delivery of a uniform beam profile on sample which reached the maximum theoretical flux

(Figure 9). When comparing the results of the MCNP study of this design to traditional collimation, several important difference are seen. There is a reduction of background beam impingement on the sample frame by as much as 10^3 as compared to the traditional design (Figure 10). The new design realizes an 87% increase in flux on the sample area (Figure 11). Beam uniformity in the new design is dramatically improved over the sample area, as the traditional design varied by as much as a factor of 4 (Figure 11).

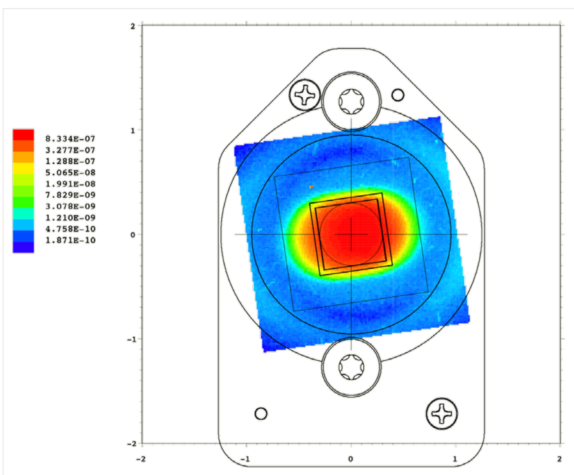

Figure 10. MCNP Study of Traditional Collimation Design, Visualization Covering 5 Orders of Magnitude

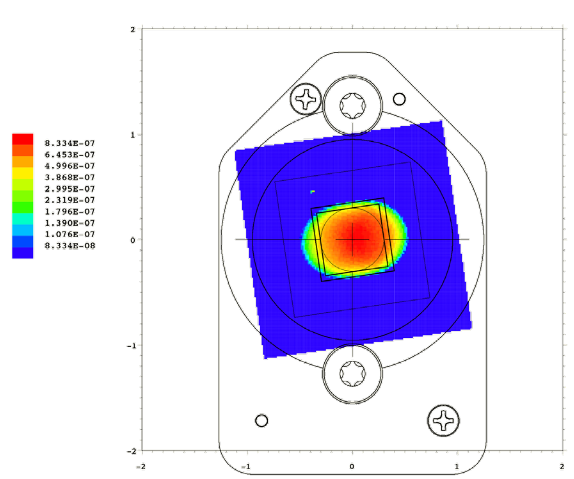

Figure 11. MCNP Study of Traditional Collimation Design, Visualization above 1/10 Delivered Max

Having the collimation geometry finalized, it was separated into 10 individual elements for fabrication. The most upstream 8 elements were fabricated from brass, with the remaining two downstream elements fabricated from tungsten. It was decided to do this because it would have been cost prohibitive to fabricate the entire collimator out of tungsten. Instead, fabricating the two downstream most elements with tungsten delivers the most return on the additional cost by enhancing the penumbra cut-off in the horizontal direction while also reducing overall background. The 10 elements were sent out for fabrication via wire EDM.

The collimation elements must be well aligned to one another and precisely aligned within the facility. Its placement with respect to the spallation target, flight path, and hotLENZ instrument is critical to proper neutron transport and optimal performance of the collimation system. To align and support the individual collimation elements as one assembly, a precision strongback was designed and fabricated to provide the necessary platform for the collimation elements. The top of the strongback is machined to a tight flatness tolerance, and a side stop is integrated into this geometry, aligning the individual collimation elements. The top of the strongback also has the proper inclination built in to match the orientation of the spallation target (Figure 12). The bottom of the strongback has an integral Maxwell kinematic clamp. This kinematic clamp interfaces with the 6DOF precision alignment system built into the collimation support structure. This alignment system is built with heavy duty, high precision micrometer cross slides and vertical stages, providing micron level 6DOF adjustment. This affords a means to accomplish the required precision alignment of the collimation system.

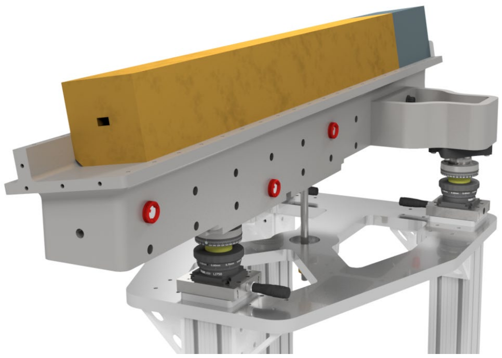

Figure 12. Collimation Elements, Strongback Structure, Alignment Fiducials, and Precision Alignment System

The final component of the new collimation system is the shutter insert. This insert is the first clean up element in the collimation system and resides in the flight path shutter within the bulk shield. Due to the misalignment of the 90L shutter axis with respect to the spallation target center, it was necessary to establish a flight path axis separate and independent from the shutter axis. Again, the 3D model compiled from all of the previous survey efforts was leveraged to carry on with the flight path axis development as well as the design of the new shutter insert. To continue the design work, the newly designed collimation ray trace data was imported into the 3D survey model. From this data, an optimized flight path axis was established to ensure an unobstructed FOV for the collimation (Figure 13). The collimation 3D ray trace data was used to define the envelope for the new shutter insert. The shutter insert geometry designed around this FOV envelope resulted in an asymmetric stepped insert to provide the proper FOV for the collimation, while cleaning up as much unwanted background beam as possible. Due to its geometry, the shutter insert was fabricated in pieces then carefully fitted together to maintain the tight tolerances necessary for proper assembly, installation, and performance (Figure 14).

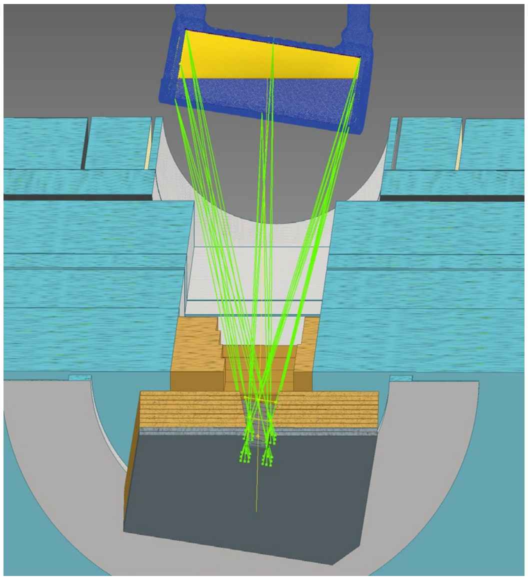

Figure 13. Orthographic Cut-through View of Flight Path Model Showing New Flight Path Axis, Collimation FOV (Green Lines), and Stepped Offset Shutter Insert

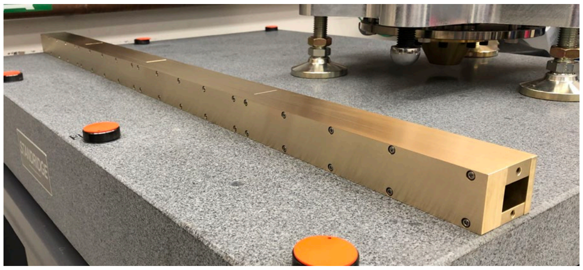

Figure 14. Assembly and Inspection of the Stepped Offset Brass Shutter Insert for FP90L

Installation of Collimation System

After fabrication, assembly, and inspection/fiducialization of the collimation system components, the installation effort was undertaken. A final nominal 3D model was created from all of the collimation design work detailed so far combined with the as-built survey data at the facility and flight path. Using this model, an alignment file was created to establish the nominal locations of the collimation system components at WNR FP90L with respect to the facility USMN (Figure 15). Nominal alignment frames within the file were used in conjunction with a laser tracker system to locate and anchor the base plate for the support structure in the experimental area. The support structure was installed and roughly aligned in the same manner. Finally, the collimation system was installed on the structure and precisely aligned to the nominal flight path axis and the absolute spallation target position/orientation within the facility (Figure 16).

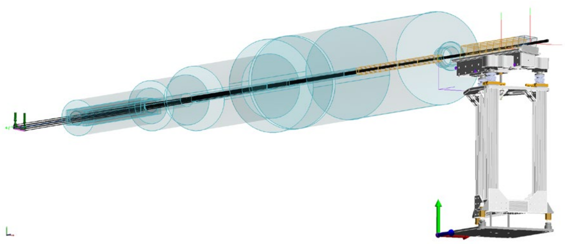

Figure 15. Visualization of Nominal Collimation Alignment

Collimator Strongback Actual::Actual Strongback Alignment			
	X	Y	Z
Translation (mm)	0.0012	0.0031	-0.0055
Rotation (deg)	0.0019	0.0060	0.0041
X Axis	1.000000	0.000071	-0.000104
Y Axis	-0.000071	1.000000	0.000033
Z Axis	0.000104	-0.000033	1.000000

Figure 16. Collimation Alignment at FP90L, Deviation from Nominal Position

Commissioning and Preliminary Results

Having successfully assembled, installed, and aligned the collimation system at WNR FP90L, the system was then commissioned. With little time before the arrival of the radioactive sample for this experiment, it was decided the preliminary evaluation of system performance would be executed with image plates. Image plates are a standard tool which have historically been utilized across the facility for neutron beam imaging. The image plates were installed in fiducialized holders which had been recently developed for integration with our metrology efforts (Figure 17). These holders were placed upstream and downstream of the collimation and surveyed with a laser tracker system. Where the fiducialized holders could not be placed, smaller plates were used which could be referenced to instrument geometry easily identified in the exposed images. The flightpath shutter was opened and the plates exposed to the beam. The plates were digitized and the image plate data was merged with the final survey data.

Figure 17. Fiducialized Image Plate Holder

Evaluation of the image plate data at the sample position indicated that the neutron beam delivered on sample agreed with the MCNP predictions very well. The beam spot was uniform in size and intensity, and showed up in the location expected (Figure 18). The data from the image plate located at 11.3m downstream is a very good diagnostic tool. Due to its long path length, this downstream image plate will clearly show any misalignments of the collimation system. Also, the rapidly expanding beam profile at this downstream location will indicate problems with the collimation geometry by magnifying any deviations from the nominal beam profile at this location. When this downstream most plate was digitized and the collimation ray trace overlaid on the data, it showed excellent agreement with the predicted beam spot profile at this location, as well as appearing where expected within the experimental area (Figure 19). The data from this downstream most image plate served to verify that that spallation target spatial data acquired from our earlier efforts (LA-UR-20-30500) is accurate, the collimation was well aligned to the spallation target, and that the results of the MCNP studies were reproduced at the flight path.

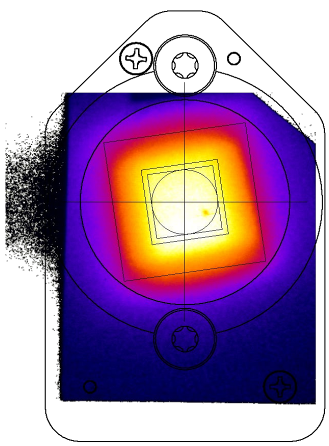

Figure 18. Actual Image Plate Data at Sample Position Overlaid on Sample Frame Drawing

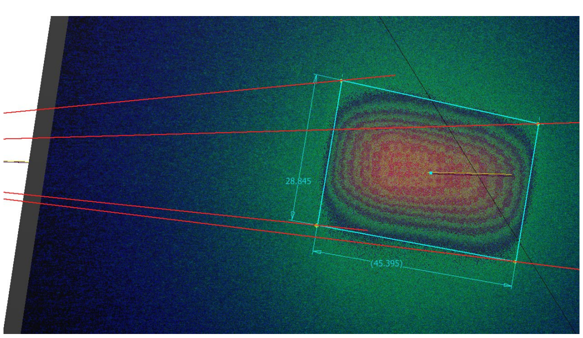

Figure 19. Actual Image Plate Data at 11.3m Combined with Survey Data. Extrapolated Ray Tracing Red, Predicted Beam Profile Light Blue

Conclusion

An advanced collimation system has been designed using state of the art 3D modeling, MCNP studies, and exploiting cutting edge metrology and survey tools. These modern survey tools and workflows have been developed for use at WNR over the past 18 months, and have shown to be very powerful for generating highly accurate spatial data sets and executing precision alignments. Without this capability, none of this work would have been possible. It has been shown that with a high resolution holistic approach to neutron transport, neutron beam delivery can be tailored to meet the specific and stringent requirements of modern high precision nuclear physics experimental programs. For this particular experimental program, we were able to tailor a neutron beam transport system to deliver a uniform beam with a specific profile reaching the maximum neutron flux possible. All this was accomplished while simultaneously reducing unwanted neutron background by several orders of magnitude. This approach to collimation design and neutron transport optimization can be applied to many other research programs and flight paths at WNR and Lujan Center, increasing the quality of neutron beams delivered across the facilities.